Department I - C Plus Plus

Modern and Lucid C++ for Professional Programmers

Week 11 – Heap Memory Management

Thomas Corbat / Felix Morgner
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- **You can safely use heap allocation**
- **You can write leak-free recursive data structures**
- **You can explain the difference between the two main smart-pointers found in the STL**

Topics

- **Recap Week 10**
- **Heap Memory Management**
  - Introduction / Motivation
  - Dangers of Raw Pointers
  - Managing Unique Objects
  - Sharing Objects
  - Recursive Data Structures

Recap Week 10

- **Define class templates completely in header files**
- **Member functions of class templates**
  - Either in class template directly
  - Or as inline function templates in the same header file
- **`static` member variables of a template class can be defined in header without violating ODR, even if included in several compilation units**
  - Since C++17 they can even be declared inside the class template, this requires the `inline` keyword

```
template <typename T>
struct staticmember {
  inline static int dummy{sizeof(T)};
};
```

```
using size_type = typename SackType::size_type;
```

- **Within the template definition you might use names that are directly or indirectly depending on the template parameter**
  - E.g. everything using `SackType::`
- **But you have to tell the compiler if one is a type**
  - In contrast to a variable or function name
- **When the `typename` keyword is required you should extract the type into a type alias**
- **Old spelling in `typedef`**

```
typedef typename SackType::size_type size_type;
```

- **Rule: Always use `this->` or the class `name::` to refer to inherited members in a template class**

```
this->bar
```

```
gotchas::bar
```

- **If the name could be a dependent name the compiler will not look for it when compiling the template definition**
- **Checks might only be made for dependent names at template usage (=template instantiation)**
  - That is sometimes the reason for lengthy error messages from template usages

- **How can we adapt a standard container by adding invariants or by extending their functionality?**
  - `SafeVector` -> no undetected out-of-bounds access
  - `IndexableSet` -> provide operator[]
  - `SortedVector` -> guarantee sorted order of elements
- **Template class inheriting from template base class**
  - And inherit ctors of standard container
  - Caution: no safe conversion to base class, no polymorphism

Heap Memory Management

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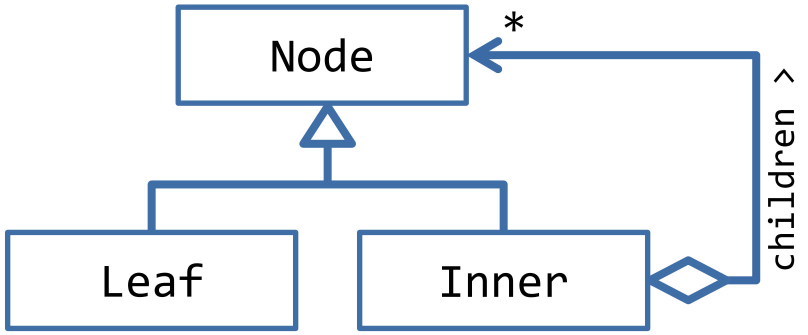
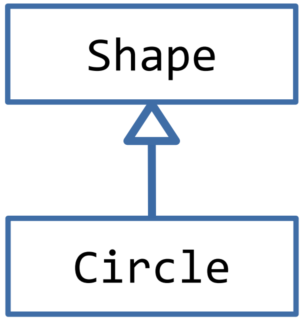
- **Stack memory is scarce**

- **It might be needed for creating object structures**
  - First think about library classes for your intended structure
  - Look into the Boost library collection if the STL is insufficient



- **For polymorphic factory functions to class hierarchies**
  - If you return a base-class "pointer" to one of its subclasses from functions

```
std::unique_ptr<Shape> circle = make_circle(x, y, r);
```



- **Always rely on library classes for managing it (if possible)**
- **Resource Acquisition Is Initialization (RAII) Idiom**
  - Allocation in the constructor
  - Deallocation in the destructor
  - Use RAII wrapper as value in local scope
  - Destructor will be called when the scoped is exited (`}`, `return` or exception)

```
struct RaiiWrapper {
  RaiiWrapper() {
    //Allocate Resource
  }
  ~RaiWrapper() {
    //Deallocate Resource
  }
};
```

- **Doooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooooon't do that!**
- **C++ allows allocating objects on the heap directly**

```
auto ptr = new int{};
std::cout << *ptr << '\n';
delete ptr;
```

- **However, if done manually you are responsible for deallocation and risk undefined behavior!**
  - Memory leaks
  - Dangling pointers
  - Double deletes
- **No garbage collection happens, it is your responsibility**

```
std::unique_ptr<X> factory(int i) {
  return std::make_unique<X>(i);
}
```

- **`std::unique_ptr<T>` obtained with `std::make_unique<T>()`**
- **`std::shared_ptr<T>` obtained with `std::make_shared<T>()`**
- **`std::make_unique<T>()` and `std::make_shared<T>()` are factory functions**
- **With these smart pointers you don't have to call `delete ptr;` yourself**
- **Still: Always prefer storing a value locally as value-type variable (stack-based or member)**

- **Used for unshared heap memory**
  - Or for local stuff that must be on the heap
    (rarely needed, e.g. for large instances and limited stack space)
  - Can be returned from a factory function
- **Only a single owner exists**
- **It can wrap to-be-freed pointers from C functions when interfacing legacy code**
- **Not best for class hierarchies**
  - Use `std::shared_ptr<Base>` instead (`unique_ptr` base classes need virtual destructor)

- **A `std::unique_ptr` cannot be copied**

```
#include <iostream>
#include <memory>
#include <utility>

std::unique_ptr<int> create(int i) {
  return std::make_unique<int>(i);
}

int main() {
  std::cout << std::boolalpha;
  auto pi = create(42);
  std::cout << "*pi = " << *pi << '\n';
  std::cout << "pi.valid? " << static_cast<bool>(pi) << '\n';
  auto pj = std::move(pi);
  std::cout << "*pj = " << *pj << '\n';
  std::cout << "pi.valid? " << static_cast<bool>(pi) << '\n';
}
```

Transfer of ownership through return by value

Explicit transfer of ownership from lvalue

`std::unique_ptr<T>` for Naked C Pointers (1/2)

- **Some C functions return pointers that must be deallocated with the function `free(ptr)`**
- **We can use `std::unique_ptr` to ensure that**
- **Example: `__cxa_demangle()` is such a function**

```
std::string demangle(std::string const & name) {
  auto cleanup = [] (char * ptr){
    free(ptr);
  };
  std::unique_ptr<char, decltype(cleanup)> toBeFreed {
    __cxxabiv1::__cxa_demangle(name.c_str(), 0, 0, 0), cleanup};
  std::string result(toBeFreed.get());
  return result;
}
```

- **If there is an exception in the context of that pointer, `free` will be called on the returned pointer**
  - No memory leak

- **A `std::unique_ptr` storing the address of the deleter function/lambda has an extra pointer and thus is twice the size**
  - Better provide a deleter type as template argument, which implies no space overhead

```
struct free_deleter {
  template<typename T>
  void operator()(T * p) const {
    free(const_cast<std::remove_const_t<T> *>(p));
  }
};

template<typename T>
using unique_C_ptr = std::unique_ptr<T, free_deleter>;

std::string plain_demangle(char const * name) {
  unique_C_ptr<char> toBeFreed{__cxxabiv1::__cxa_demangle(name, 0, 0, 0)};
  std::string result(toBeFreed.get());
  return result;
}
```

- **As member variable:**
  - To keep a polymorphic reference instantiated by the class or passed in as `std::unique_ptr` and transferring ownership
- **As local variable:**
  - To implement RAII
  - Can provide custom deleter function as second template argument to type that is called on destruction
- **`std::unique_ptr<T> const p{new T{}}; // local`**
  - Cannot transfer ownership
  - Cannot leak!

- **`std::unique_ptr` allows only one owner and cannot be copied, but only returned by value**
- **`std::shared_ptr` works more like Java's references**
  - It can be copied and passed around
  - The last one ceasing to exist deletes the object
- **You create `std::shared_ptr` and associated objects of type `T` using `std::make_shared<T>(...)`**
- **`std::make_shared<T>` allows all `T`'s public constructor's parameters to be used**

```
struct Article {
Article(std::string title, std::string content);
  //..
};

Article cppExam{"How to pass CPl?", "In order to pass the C++ exam, you have to..."};

std::shared_ptr<Article> abcPtr = std::make_shared<Article>("Alphabet", "ABCDEFGHIJKLMNOPQRSTUVXYZ");
```

What is it for?

- If you really need heap-allocated objects, because you create your own object networks you can use `std::shared_ptr<T>`
- If you need to support run-time polymorphic container contents or class members that can not be passed as reference, e.g., because of lifetime issues
- Factory functions returning `std::shared_ptr` for heap allocated objects
- But first check if alternatives are viable:
  - (const) references as parameter types or class members (to surviving objects!)
  - Plain member objects or containers with plain class instances

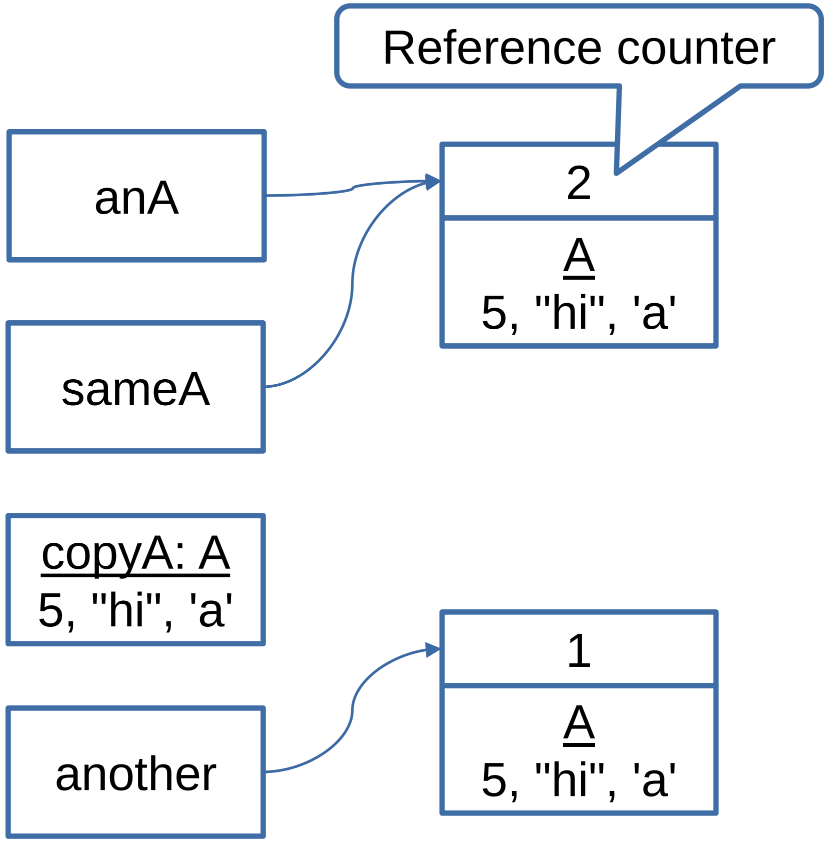
`std::shared_ptr` Example

- **If you really need to keep something explicitly on the heap, use a factory**

```
struct A {
  A(int a, std::string b, char c);
};

auto createA() {
  return std::make_shared<A>(5, "hi", 'a');
}

int main(){
  auto anA = createA();
  auto sameA = anA; //second pointer to same object
  A copyA{*sameA}; //copy ctor.
  auto another = std::make_shared<A>(copyA); //copy ctor on heap
}
```



- **Use `std::ostream`, just as an example for a base class**
  - And a very primitive factory function.
  - The concrete type is required as template argument for `make_shared`

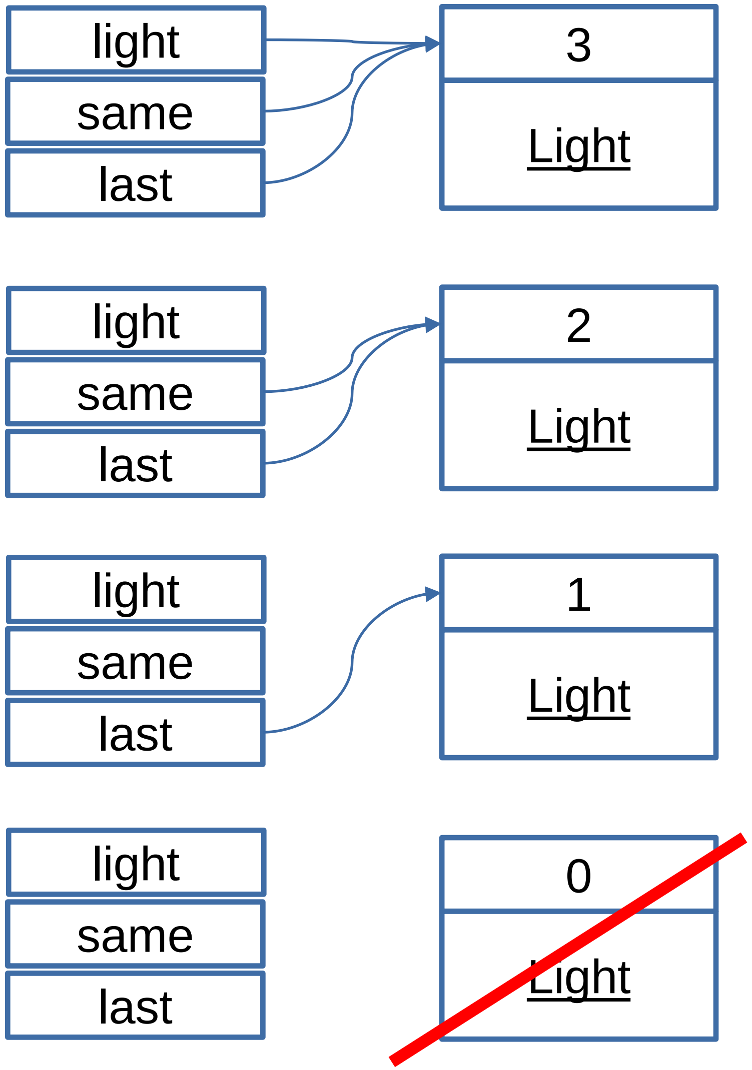
```
std::shared_ptr<std::ostream> os_factory(bool file) {
  using namespace std;
  if (file) {
    return make_shared<ofstream>("hello.txt");
  } else {
    return make_shared<ostringstream>();
  }
}

int main(){
  auto out = os_factory(false);
  if (out) {
    (*out) << "hello world\n";
  }
  auto fileout = os_factory(true);
  if (fileout) {
    (*fileout) << "Hello, world!\n";
  }
}
```

- Last `std::shared_ptr` handle destroyed/reset will delete the allocated object

```
struct Light {
  Light() {
    std::cout << "Turn on\n";
  }
  ~Light() {
    std::cout << "Turn off\n";
  }
};

int main() {
  auto light = std::make_shared<Light>();
  auto same = light;
  auto last = same;
  light.reset();
  same.reset();
  last.reset();
}
```

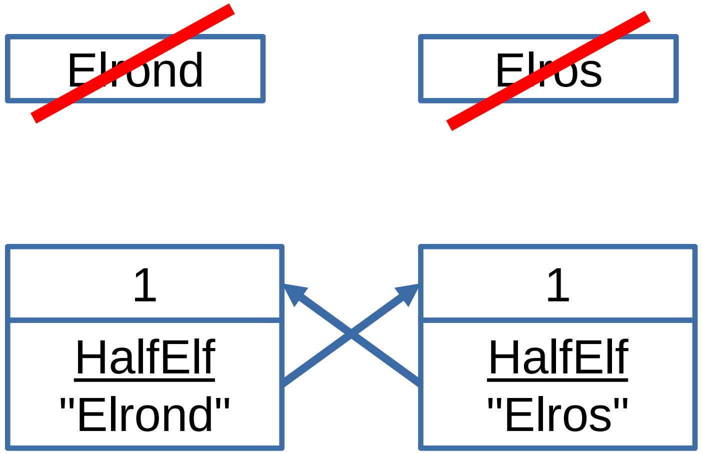


- Last `std::shared_ptr` handle destroyed will delete allocated object

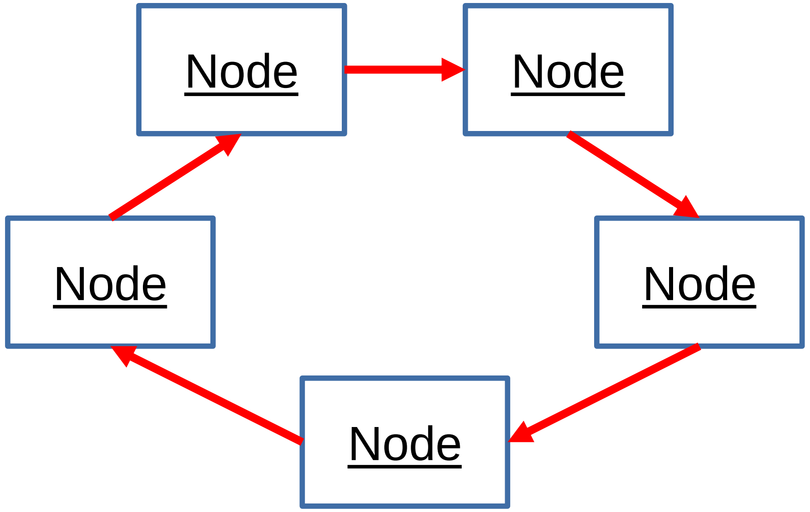
```
using HalfElfPtr = std::shared_ptr<struct HalfElf>;

struct HalfElf {
  explicit HalfElf(std::string name) : name{name}{}
  std::string name{};
  std::vector<HalfElfPtr> siblings{};
};

void middleEarth() {
  auto elrond = std::make_shared<HalfElf>("Elrond");
  auto elros = std::make_shared<HalfElf>("Elros");
  elrond->siblings.push_back(elros);
  elros->siblings.push_back(elrond);
}
```



- Last `std::shared_ptr` handle destroyed will delete allocated object
- If instances of a class hierarchy are always represented by a `std::shared_ptr<base>` but created through `std::make_shared<concrete>()` the destructor no longer needs to be virtual
  - `std::shared_ptr` memorizes concrete destructor for deletion on construction time in `std::make_shared<concrete>`
- `std::shared_ptr` can lead to object cycles no longer cleared, because of circular dependency
  - `std::weak_ptr` breaks such cycles



Example: Parents and Children

Creating cycles with std::shared_ptr

Breaking cylcles with std::weak_ptr

Acquiring std::shared_ptr to this with std::enable_shared_from_this

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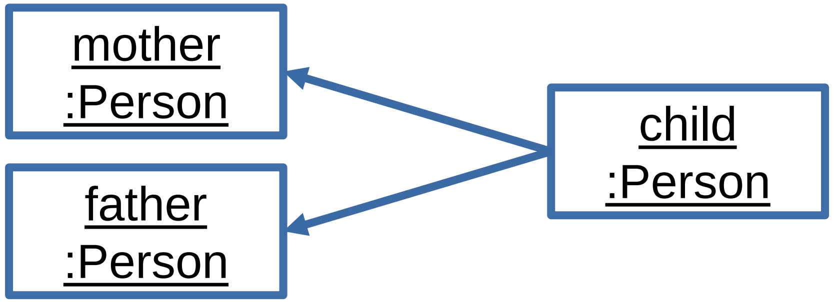
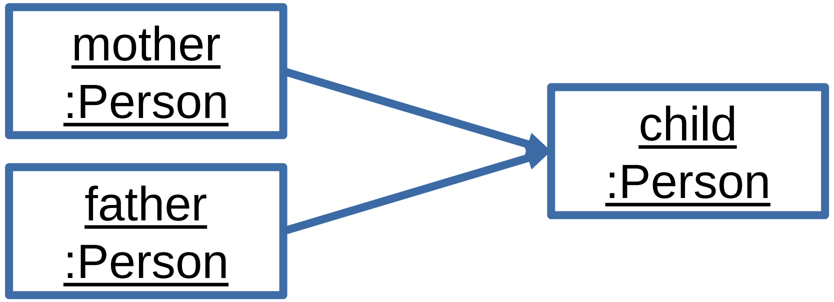
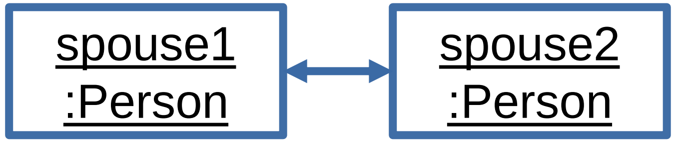
- **Create a class `Person` that represents a person**
  - Each `Person` knows about its parents (father/mother) if they are still alive



  - Each `Person` knows about its children



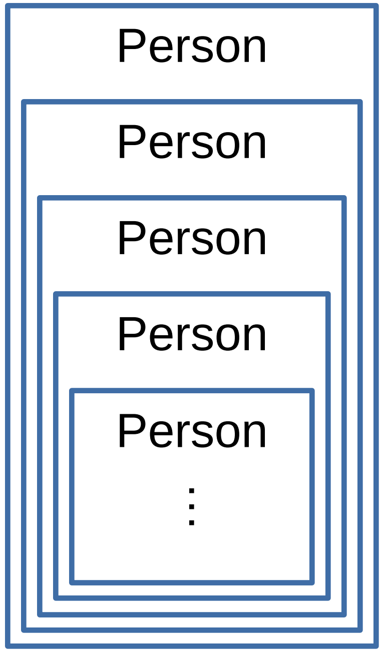
  - Each `Person` can be married



- **This results in cycles between spouses and between parents and children!**

- **Observation: You cannot use direct members (`Persons` as value members)**
  - This would incur copying `Persons`
  - The `Person` class would be recursive and therefore infinite

```
struct Matryoshka {
  Matryoshka nested;
};
```

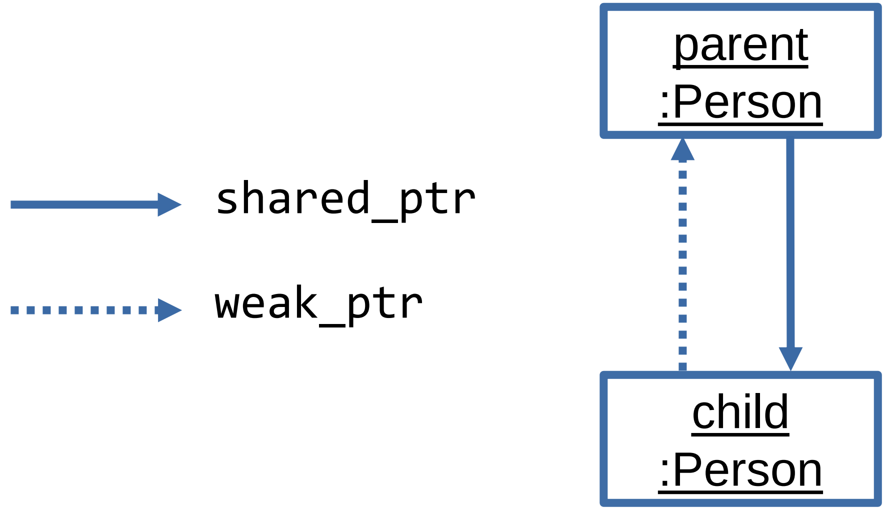


- **We need an indirection (Smart Pointer)**

```
struct Matryoshka {
  std::shared_ptr<Matryoshka> nested;
};
```

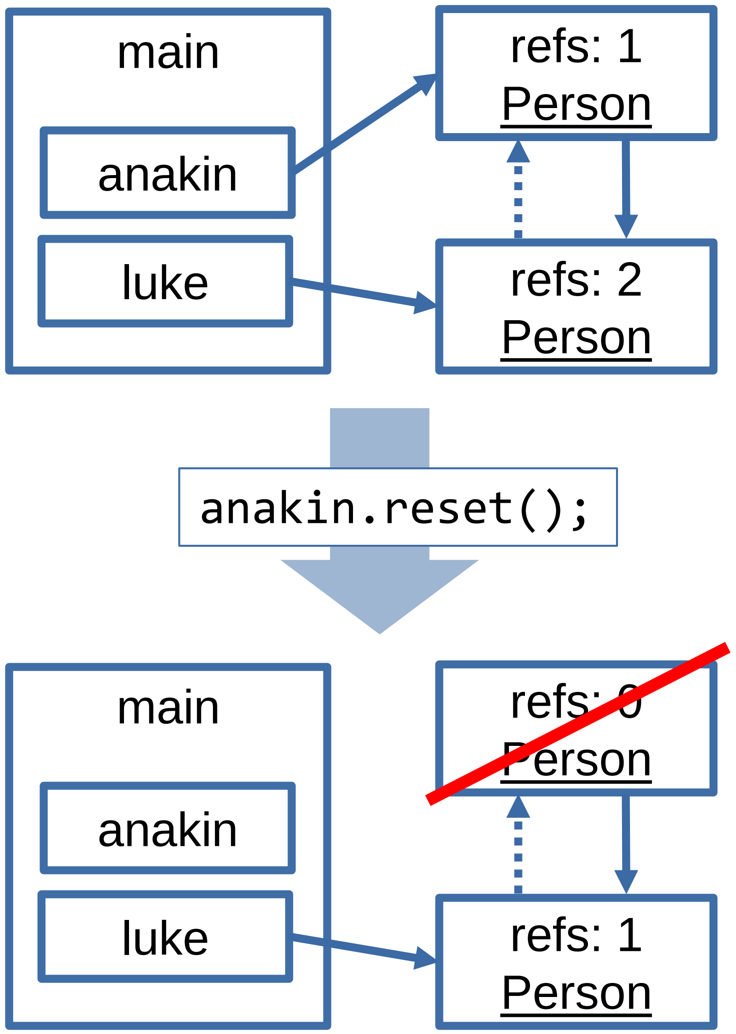
- **The `std::shared_ptr` cycles need to be broken**
- **`std::weak_ptr` does not allow direct access to the object**
  - With `lock()` a `std::shared_ptr` to the object can be acquired

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;
};
```



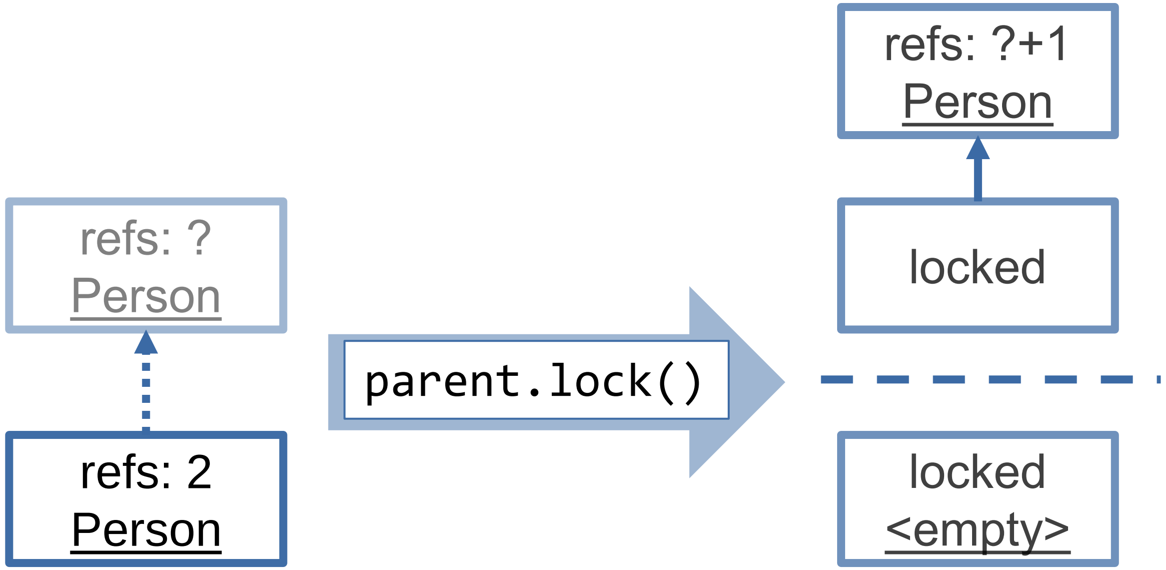
- **The `std::shared_ptr` cycles need to be broken**

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;
};

int main() {
  auto anakin = std::make_shared<Person>();
  auto luke = std::make_shared<Person>();
  anakin->child = luke;
  luke->parent = anakin;
  //...
}
```



- **A `std::weak_ptr` does not know whether the pointee is still alive**
  - `std::weak_ptr::lock()` returns a `std::shared_ptr` that either points to the alive pointee or is empty

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;

  void Person::acquireMoney() const {
    auto locked = parent.lock();
    if (locked) {
      begForMoney(*locked);
    } else {
      goToTheBank();
    }
  }
};
```



Spawning Children from Parents

- **It would be nice if parents could spawn their own children**
  - We need a `std::weak_ptr/std::shared_ptr<Person>` to the this object, to assign `child.parent`

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;

 auto spawn() {
    child = std::make_shared<Person>();
    child->parent = ???;
    return child;
  }
};
```

```
struct Person : std::enable_shared_from_this<Person> {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;

  auto spawn() {
    child = std::make_shared<Person>();
    child->parent = weak_from_this();
    return child;
  }
};
```

Curiously Recurring Template Pattern (CRTP)

- **Publicly deriving from `std::enable_shared_from_this<T>` provides the member functions `weak_from_this()` and `shared_from_this()`**
  - It internally stores a `std::weak_ptr` to the this object

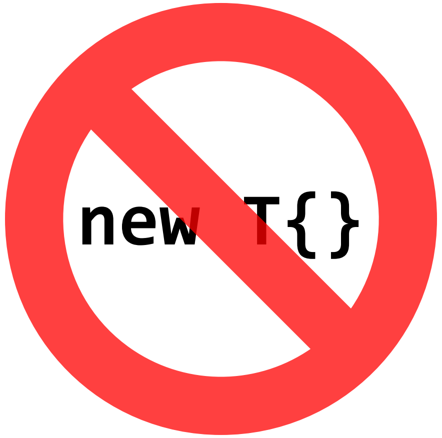
Having Multiple Children

- **Smart pointers can be stored in standard containers, like `std::vectors`**
- **An alias for a `Person` pointer that can be used in the type itself requires a forward declaration**

```
using PersonPtr = std::shared_ptr<struct Person>;

struct Person {
  //...
private:
  std::vector<PersonPtr> children;
  std::weak_ptr<Person> mother;
  std::weak_ptr<Person> father;
};
```

Summary

- **Prefer `std::unique_ptr`/`std::shared_ptr` for heap-allocated objects over `T *`**
- **Use `std::vector` and `std::string` instead of heap-allocated arrays**
- **Avoid circular object dependencies when creating object structures with `std::shared_ptr`**
  - This requires deliberate breaking of cycles using `std::weak_ptr` to get rid of the instantiated objects
- **Copying/destroying `std::shared_ptr` is slow due to atomic counter**



Use `nullptr`